

Accelerator
Neutrinos and
the 3-flavor
Paradigm

Mary Bishai
Brookhaven
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Laboratory

Introduction
Neutrino Mixing
Long Baseline ν
Oscillations

Accelerator ν
Experiments
Beams
Which Baseline?

LBNE

Other PX
Opportunities

Summary and
Conclusions

Accelerator Neutrinos and the 3-flavor Paradigm

Snowmass Workshop on Frontier Capability, BNL, April 17
2013

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April 17, 2013

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NEUTRINO MIXING AND OSCILLATIONS

Neutrinos have Flavors

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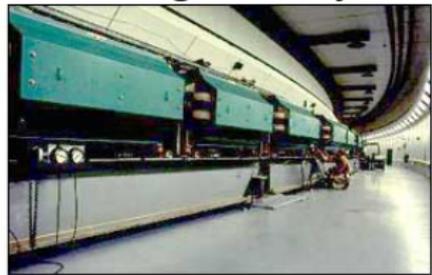
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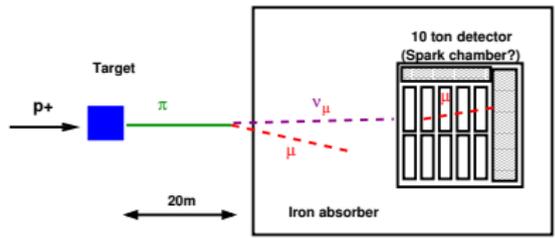
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1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi \rightarrow \mu \nu_x$



The AGS



Making ν 's

Result: 40 neutrino interactions recorded in the detector, 6 of the resultant particles were identified as background and 34 identified as

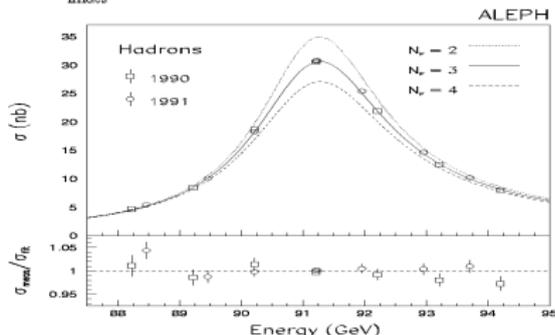
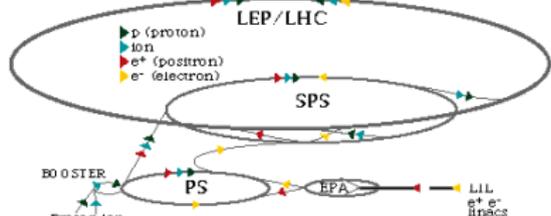
$$\mu \Rightarrow \nu_x = \nu_\mu$$

The first successful accelerator neutrino experiment was at the AGS.

Number of Neutrino Flavors: Particle Colliders

1980's - 90's: The number of neutrino types is precisely determined from studies of Z^0 boson properties produced in e^+e^- particle colliders. $N_\nu = 2.984 \pm 0.008$

The LEP e^+e^- collider at CERN, Switzerland



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1957,1967: **B. Pontecorvo** proposes that neutrinos could oscillate:

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_a(t) = \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t)$$

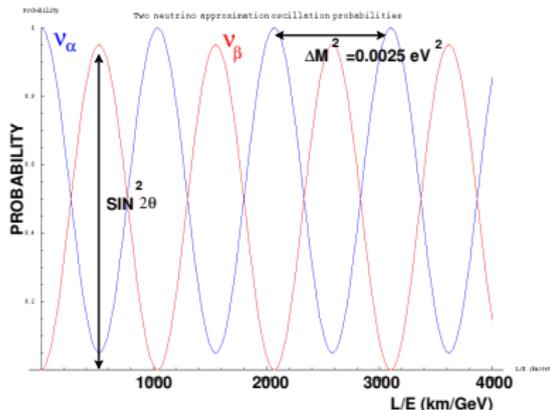
$$\begin{aligned} P(\nu_a \rightarrow \nu_b) &= |\langle \nu_b | \nu_a(t) \rangle|^2 \\ &= \sin^2(\theta) \cos^2(\theta) |e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned}$$

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m_{21}^2 L}{E}$$

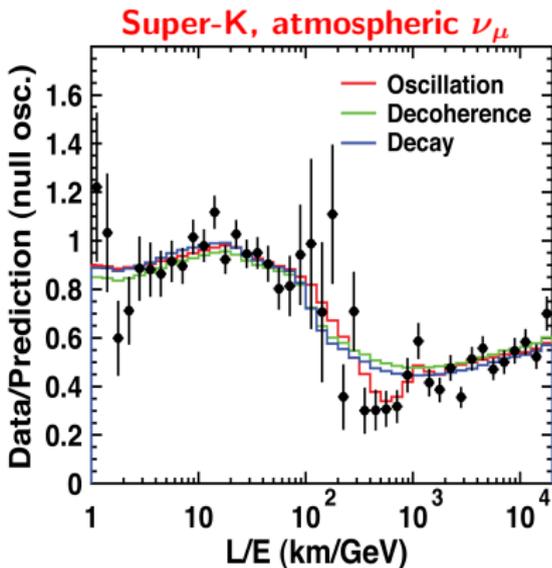
where $\Delta m_{21}^2 = (m_2^2 - m_1^2)$ in eV^2 ,
 L (km) and E (GeV).

Observation of oscillations

implies non-zero mass eigenstates



Two Different Mass Scales!



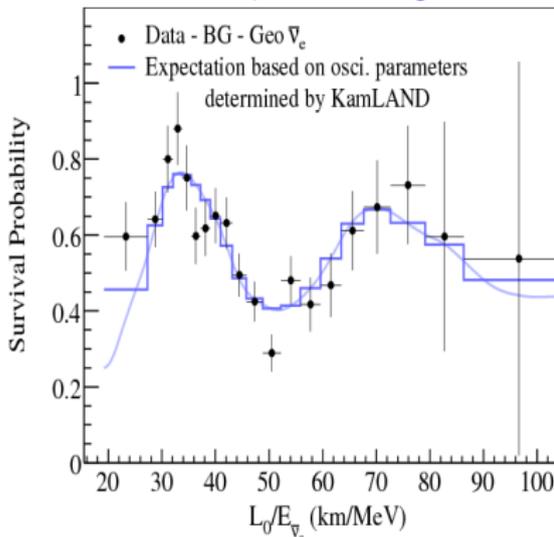
Global fit 2013:

$$\Delta m_{\text{atm}}^2 = 2.43_{-0.10}^{+0.06} \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{\text{atm}} = 0.386_{-0.21}^{+0.24}$$

Atmospheric L/E \sim 500 km/GeV

KamLAND, reactor $\bar{\nu}_e$



Global fit 2013:

$$\Delta m_{\text{solar}}^2 = 7.54_{-0.22}^{+0.26} \times 10^{-5} \text{ eV}^2$$

$$\sin^2 \theta_{\text{solar}} = 0.307_{-0.16}^{+0.18}$$

Solar L/E \sim 15,000 km/GeV

Neutrino Mixing: 3 flavors, 3 amplitudes, 2 mass scales, and a CP violating phase

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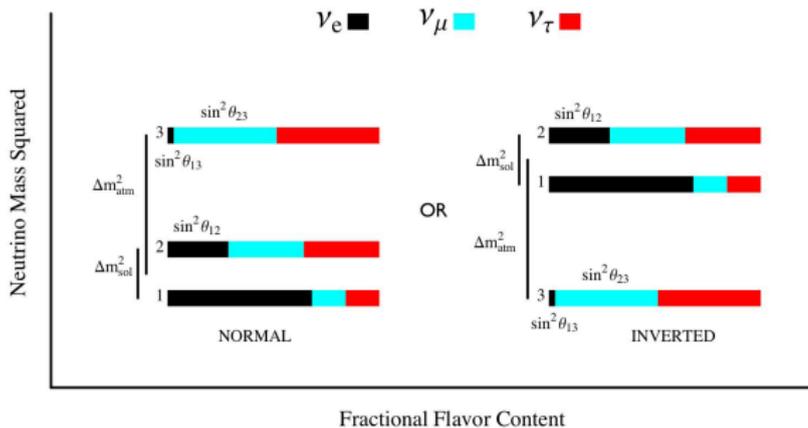
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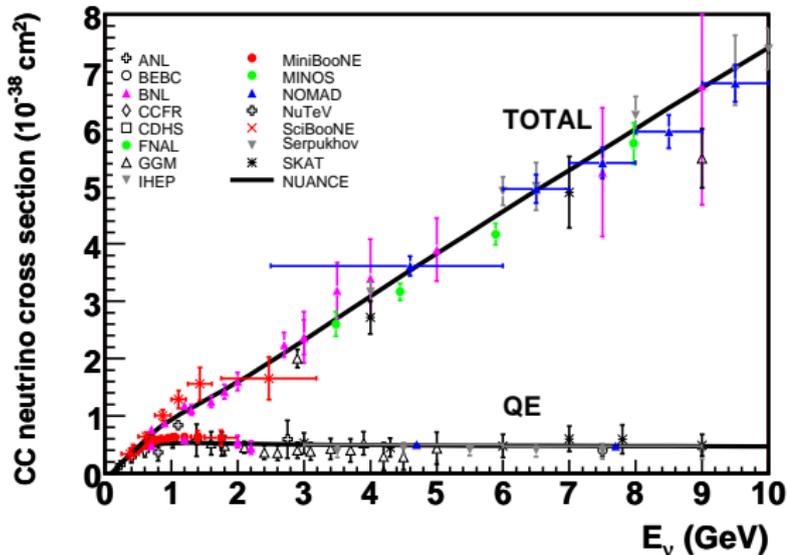
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Parameter	Value (neutrino PMNS matrix)	Value (quark CKM matrix)
θ_{12} (solar)	$34 \pm 1^\circ$	$13.04 \pm 0.05^\circ$
θ_{23} (atm.)	$38 \pm 1^\circ$	$2.38 \pm 0.06^\circ$
θ_{13}	$8.9 \pm 0.5^\circ$	$0.201 \pm 0.011^\circ$
$\Delta m_{\text{solar}}^2$	$+(7.54 \pm 0.22) \times 10^{-5} \text{ eV}^2$	
$ \Delta m_{\text{atm.}}^2 $	$(2.43^{+0.10}_{-0.06}) \times 10^{-3} \text{ eV}^2$	
δ_{CP}	$-170 \pm 54^\circ$	$m_3 \gg m_2$ $67 \pm 5^\circ$

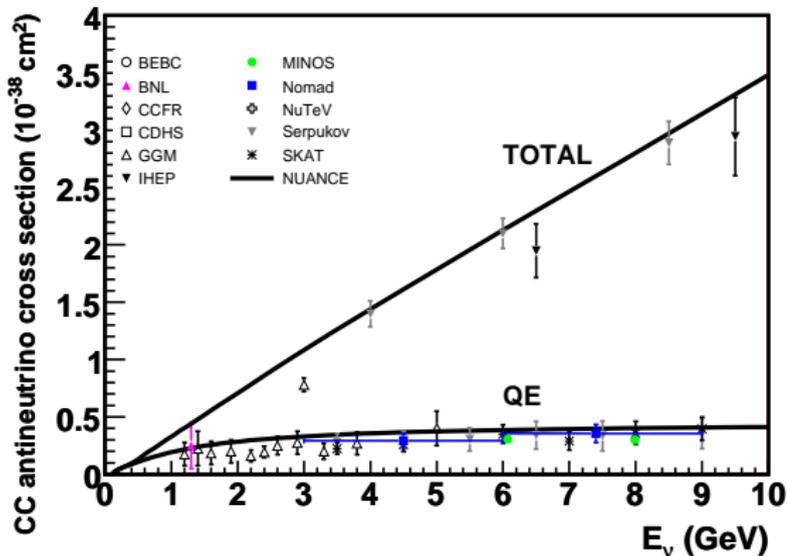
Unknown: Is $m_1 < m_3$ or vice versa?. Whats the value of δ_{CP} ?

Neutrino CC cross-sections are very small and scale with energy:
Neutrino cross-sections



**Long baseline oscillations over 100's km and ≥ 200 MeV
energies needed to probe CPV**

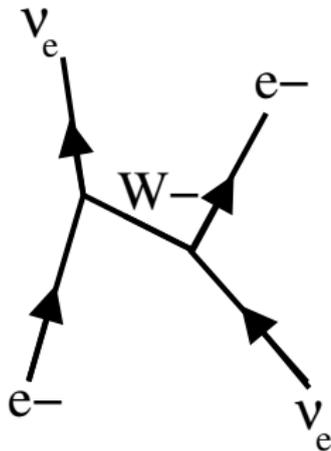
Neutrino CC cross-sections are very small and scale with energy:
Anti-neutrino cross-sections



**Long baseline oscillations over 100's km and ≥ 200 MeV
energies needed to probe CPV**

Matter Effect on Neutrino Oscillation

1978 and 1986: L. Wolfenstein, S. Mikheyev and A. Smirnov propose the scattering of ν_e on electrons in matter adds a coherent forward scattering amplitude to neutrino oscillation amplitudes. This acts as a refractive index \Rightarrow **neutrinos in matter have different effective mass than in vacuum.**



The matter effect on ν_e scattering can be used to detect the unknown neutrino mass ordering using $\nu_x \rightarrow \nu_e$ oscillations through matter

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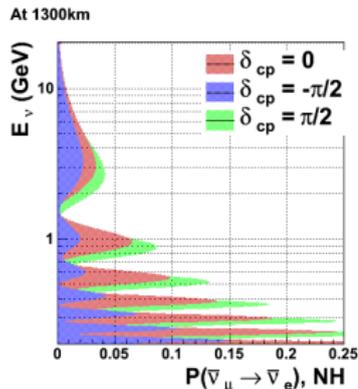
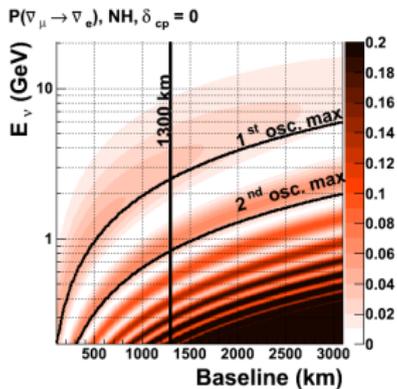
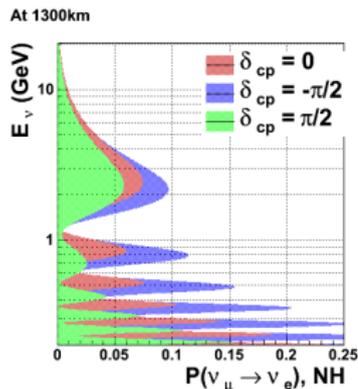
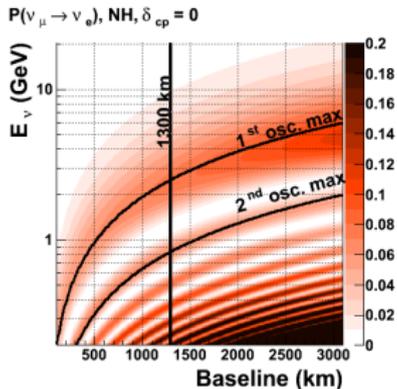
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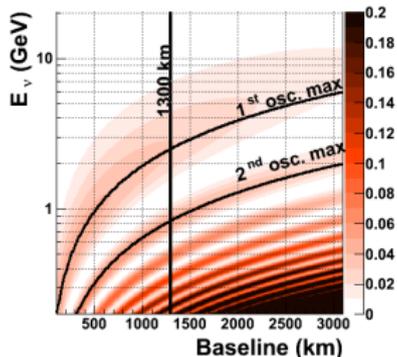
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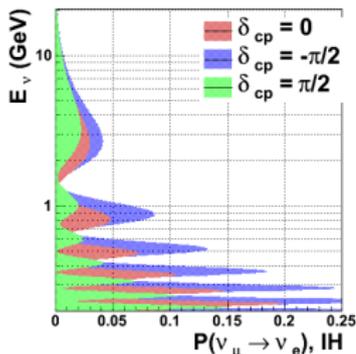
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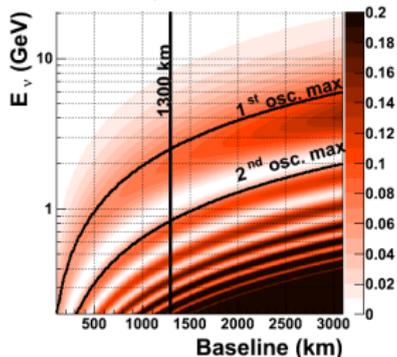
$P(\nu_\mu \rightarrow \nu_e)$, IH, $\delta_{cp} = 0$



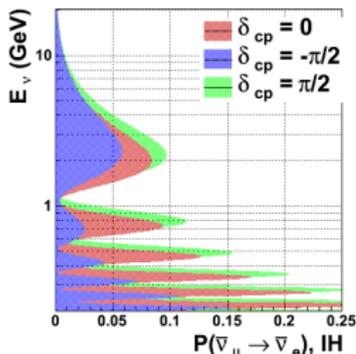
At 1300km



$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$, IH, $\delta_{cp} = 0$



At 1300km



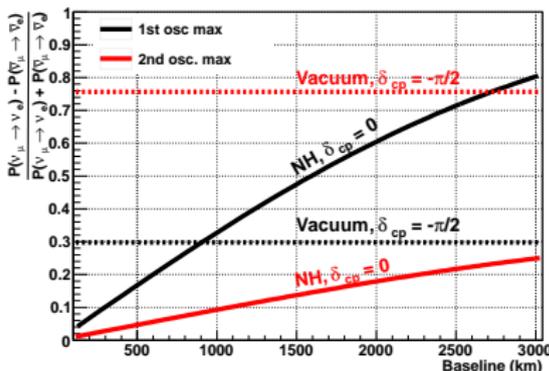
CP and Matter Asymmetries vs. Baselines for fixed L/E

The charge-parity (CP) asymmetry is defined as

$$A_{cp} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

$$A_{cp} \sim \frac{\cos \theta_{23} \sin 2\theta_{12} \sin \delta}{\sin \theta_{23} \sin \theta_{13}} \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) + \text{matter effects}$$

Z. Parsa, W. Marciano, BNL



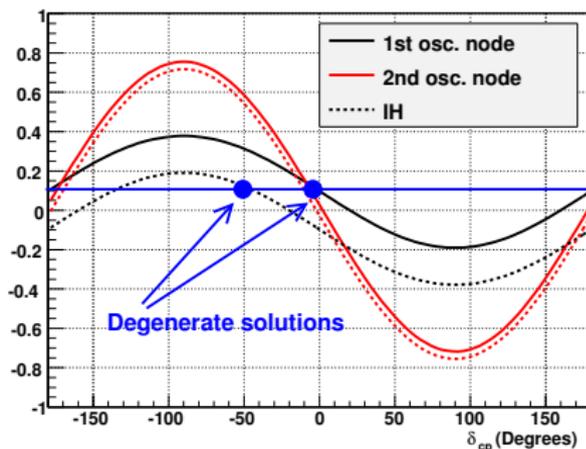
Matter and CP asymmetries have opposite effects at the 1st and 2nd oscillation maxima.

$\nu_\mu \rightarrow \nu_e$ oscillation maxima occur at

$$E_\nu^n (\text{GeV}) = \frac{2.5 \Delta m_{32}^2 (\text{eV}^2) L (\text{km})}{(2n - 1)\pi} \quad n = 1, 2, 3 \dots$$

L = 290km

Total Asymmetry at 290km



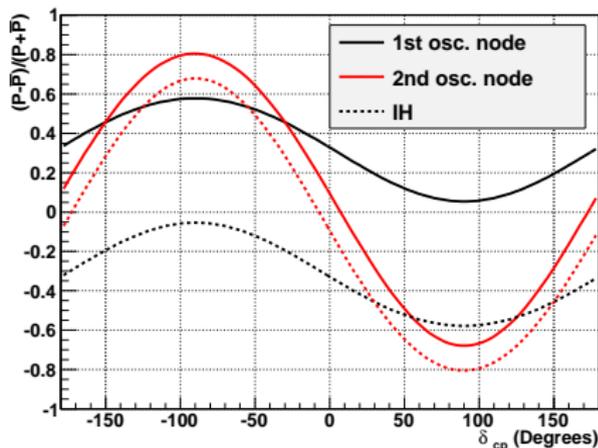
At short baselines, irreducible degeneracies with MH, δ_{cp} at E_1

$\nu_\mu \rightarrow \nu_e$ oscillation maxima occur at

$$E_\nu^n (\text{GeV}) = \frac{2.5 \Delta m_{32}^2 (\text{eV}^2) L (\text{km})}{(2n - 1)\pi} \quad n = 1, 2, 3, \dots$$

L = 1000km

Total Asymmetry at 1000km



A baseline $> 1000\text{km}$ is needed separate MH from δ_{cp}

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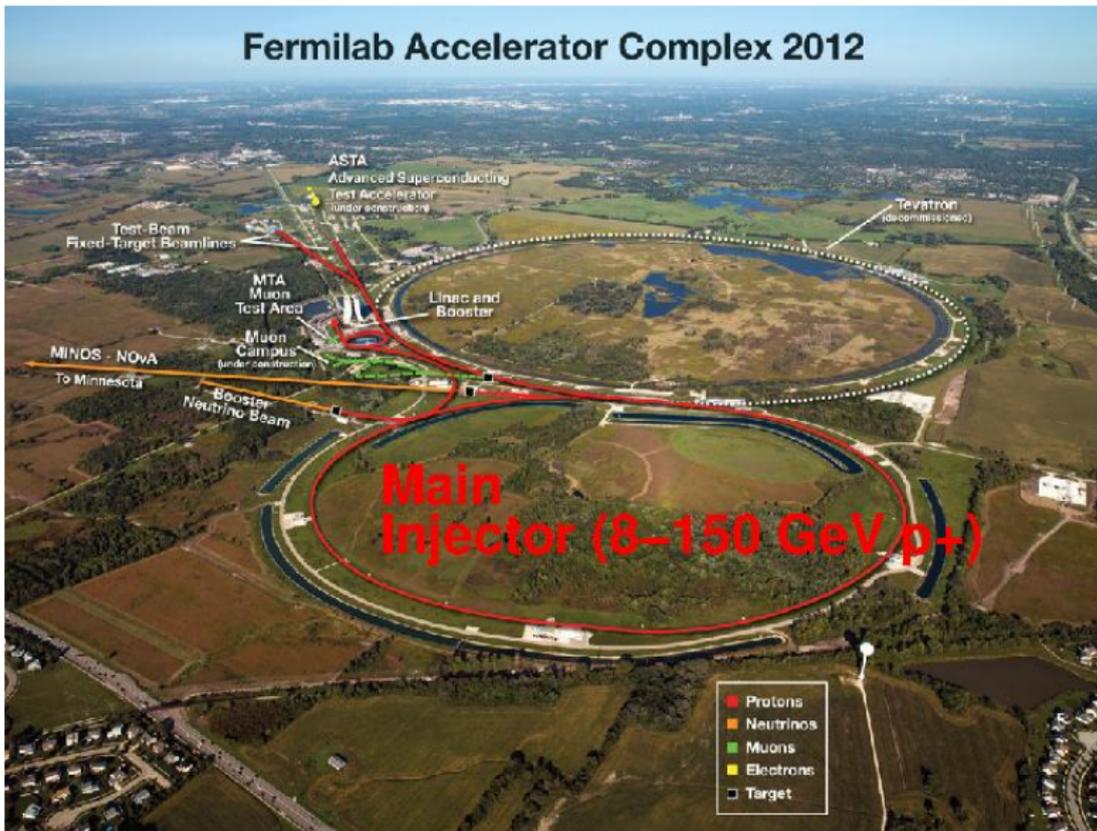
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ACCELERATOR ν Experiments

The Fermilab Accelerator Complex 2012



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Fermilab Proton Plan

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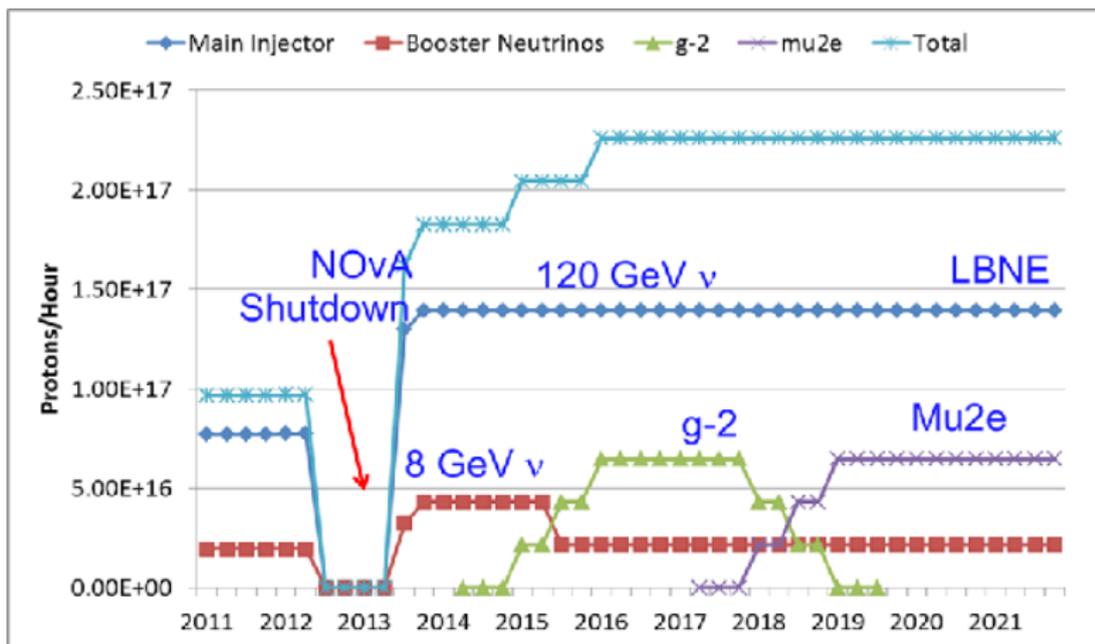
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Fermilab proton improvement plan: MI: 700 kW at 120 GeV by 2014

Future plans at Fermilab: Project X

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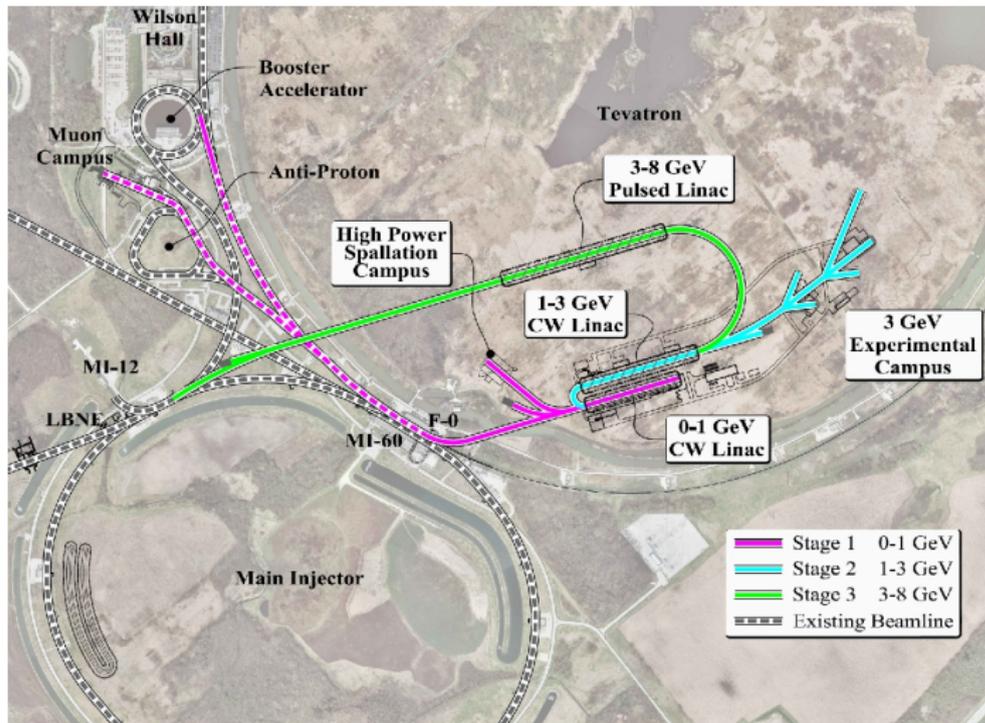
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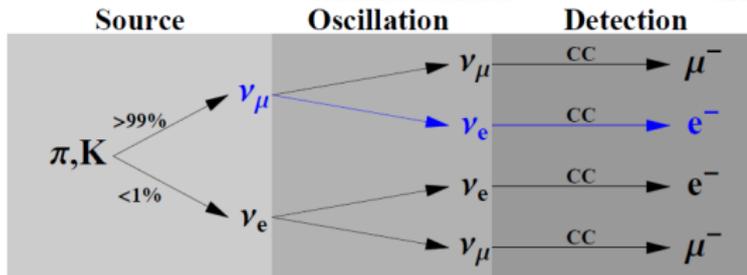
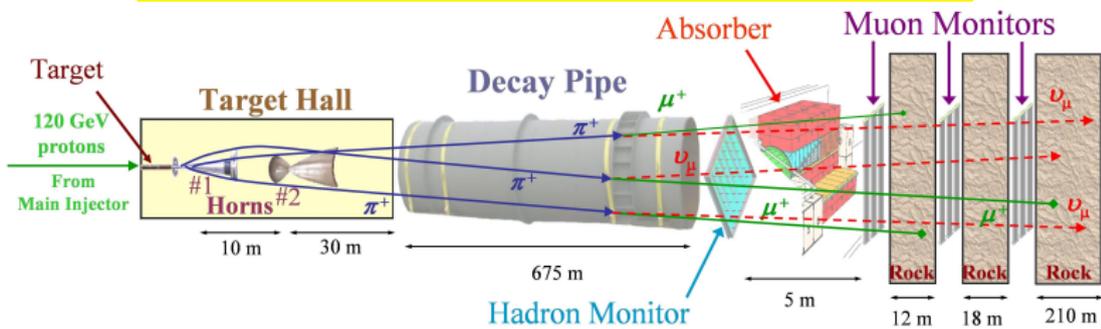
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Beyond 2025?: 2.3 MW at 60-120 GeV

Neutrinos at the Main Injector (NuMI)

High power TUNABLE conventional neutrino beam:



NuMI as built cost (2004): ~ \$115 M (did not include all labor costs!!!)

> 3 × more expensive in FY12 \$!

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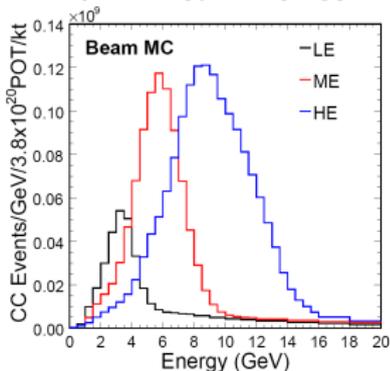
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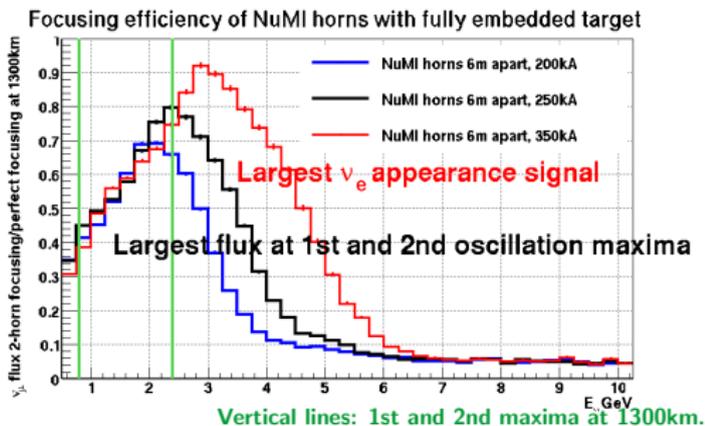
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How Good are Horn Focused ν Beams?

NuMI Beam Tunes



Comparison of ν spectra with perfect and NuMI focusing:



NuMI horn focusing $\geq 70\%$ efficient for $2 < E_\nu < 10\text{GeV}$ beams

Can cover broad 1st osc. max. with NuMI style beams for $L > 1000\text{km}$.

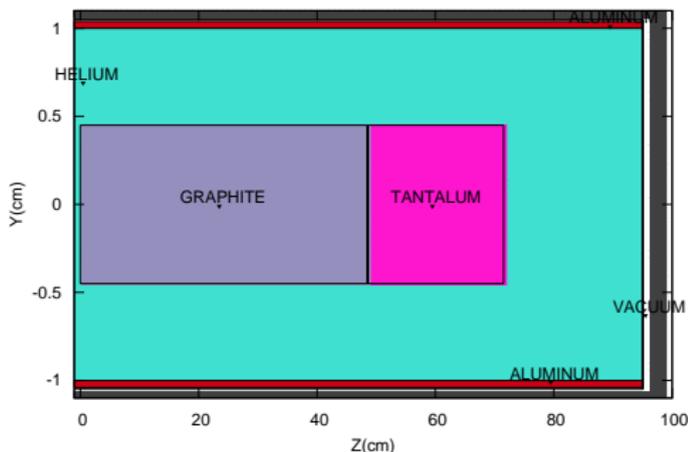
CP effects are largest at 2nd max: IF INNOVATIONS NEEDED

focusing of lower P_π , more power at lower E_p , innovative target designs

Target Innovations: Hybrid Low/High-Z Target (M. Bishai)

Combination of low-Z material upstream and high-Z material downstream, or nested target: high-Z shell with a low-Z core.

HYBRID GRAPHITE-TANTALUM TARGET 1 Y-Z



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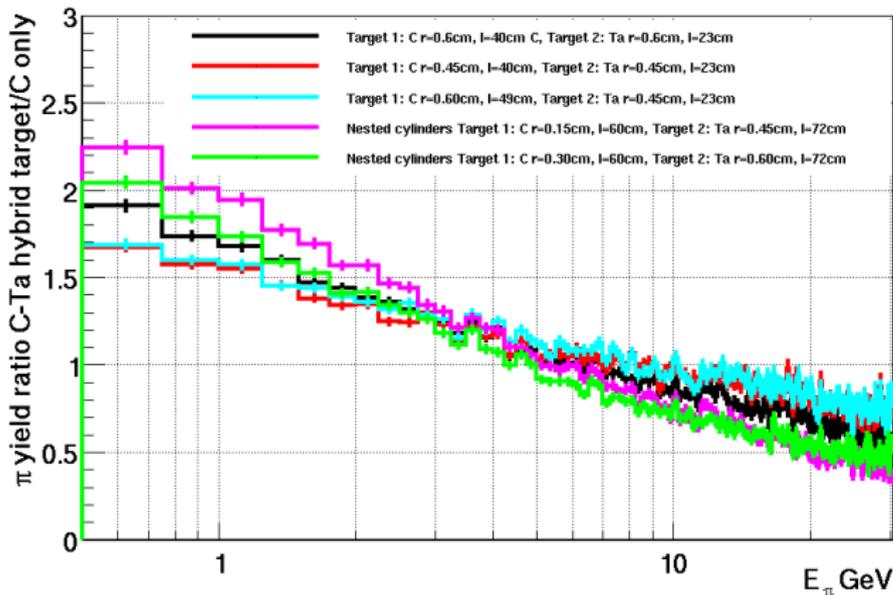
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Target Innovations: Hybrid Low/High-Z Target (M. Bishai)

1) Increases low energy π production 2) shorter target = better focus

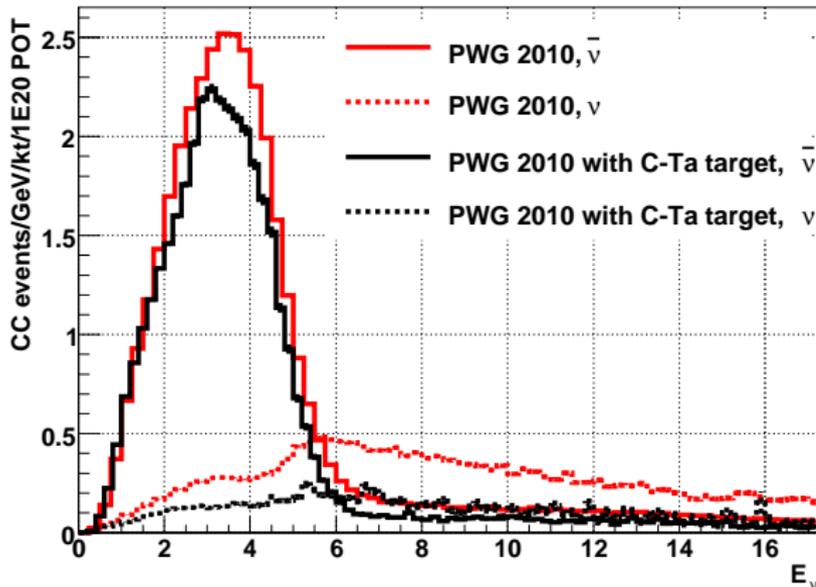
Pion yields from a hybrid C-Ta target at 120 GeV



Target Innovations: Hybrid Low/High-Z Target (M. Bishai)

3) Reduces wrong sign contamination in $\bar{\nu}$ beam

Impact of a hybrid target on wrong sign contaminant



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Neutrino Factories: $\nu_e \rightarrow \nu_\mu$ Oscillations

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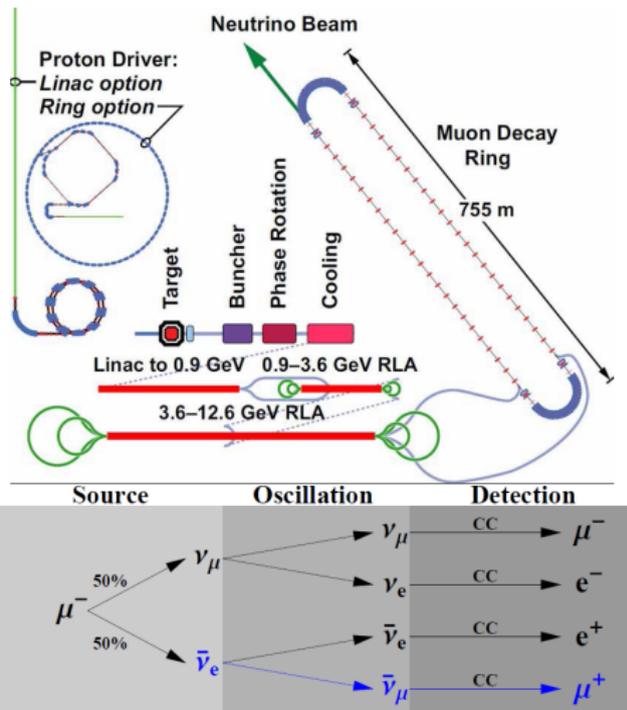
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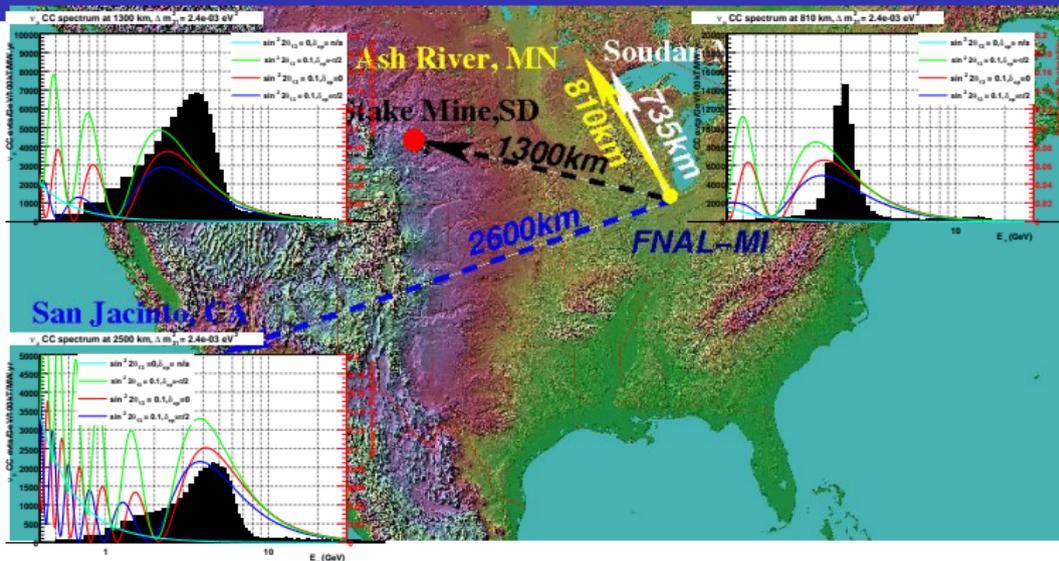
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How many μ/p^+ can be collected?

State-of-the-art from mu2e is $\mathcal{O}(10^{-3})$ at 8 GeV

Superbeam Baselines in the U.S.



CC event rates per 100kt.MW.yrs (1 MW.yr = 1×10^{21} p.o.t) for $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$, NH:

Expt	ν_μ CC	ν_μ CC osc	ν_μ NC	ν_e beam	$\nu_\mu \rightarrow \nu_e$	$\nu_\mu \rightarrow \nu_\tau$
Ash River 810km	18K	7.3K	3.6K	330	710	TBD
Hmstk 1300km	29K	11K	5.0K	280	1100	TBD
CA 2500km	11K	2.9K	1.6K	85	760	TBD

Need MW beams and 100 kton detectors regardless of baseline!

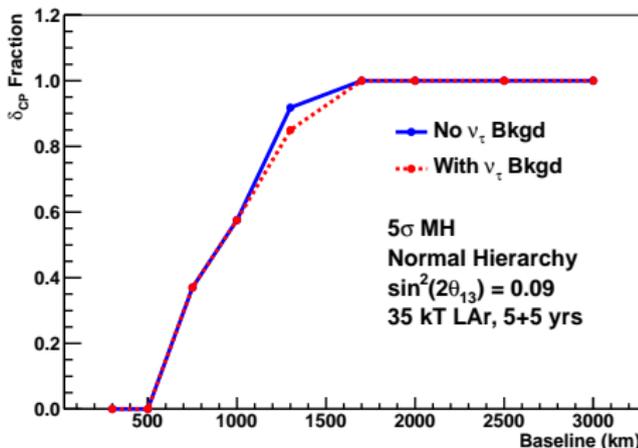
Sensitivities vs Baseline

Starting from the MI 120 GeV, we produced an optimized horn focused beam based on NuMI designs for each baseline. For shorter baselines we used off-axis angles. **For 35 kTon LAr-TPC.**

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Mass hierarchy sensitivity at $\geq 5\sigma$

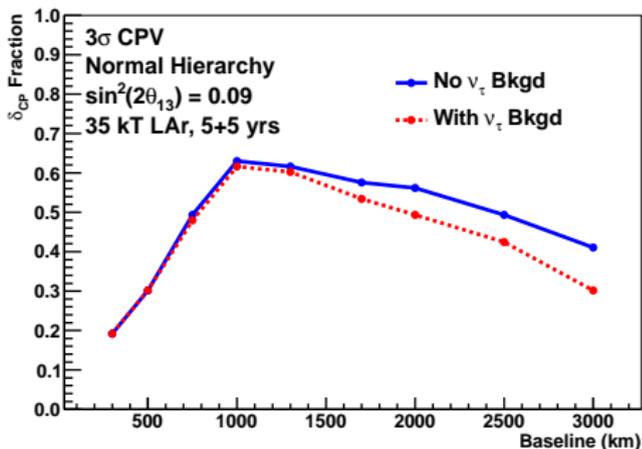


Baselines of 1500-1700km sufficient to resolve MH

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Starting from the MI 120 GeV, we produced an optimized horn focused beam based on NuMI designs for each baseline. For shorter baselines we used off-axis angles. **For 35 kTon LAr-TPC.**

CP violation sensitivity at 3σ



Baselines of 1000-1500km best CPV sensitivity

The Long Baseline Neutrino Experiment

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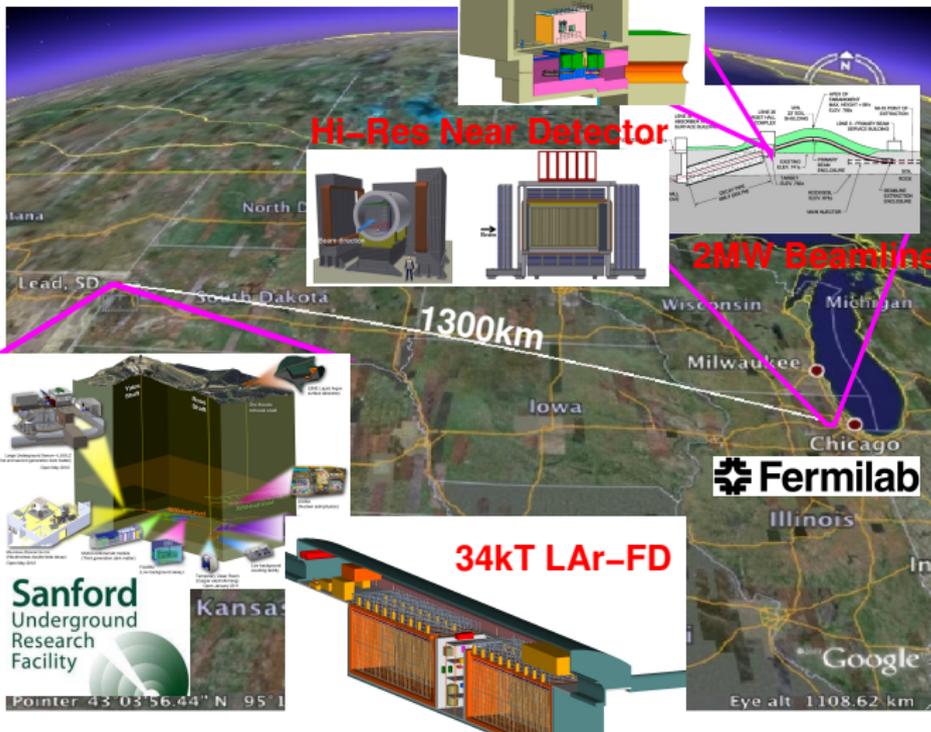
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Tunable neutrino beam

Hi-Res Near Detector

2MW Beamline

34kT LAr-FD



~ 350 people, 60 institutions from US, India, Italy, Japan, UK

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Conclusions

- **US-DOE has asked us to phase LBNE with the first phase \sim \$850M. This has been given a high priority in the US. The full cost is \sim \$1.4B.**
- **We have chosen to proceed with the most important aspect of the experiment: 1300 km baseline and the full capability beam. To keep the project cost down we chose to consider a 10 kt LAr detector on the surface.**
- **Construction will start on the beam first with site investigation to begin this year !**
- **The goal of the first phase is to place this detector underground and have a full capability near detector.**
- **New partnerships will enable this expanded scope in a timely way. The US-DOE is very supportive of this strategy.**

Specific strawman plan

Assume DOE investment at \$867M

Additional investment (TPC)	capability added	science gained	science priority
+\$150M	Underground placement	ATM nus, p-decay, SN	very high
+\$150M	Near detector	Precision physics, near detector phys	very high
+\$200M	Full far detector	Precision CP measurement	very high

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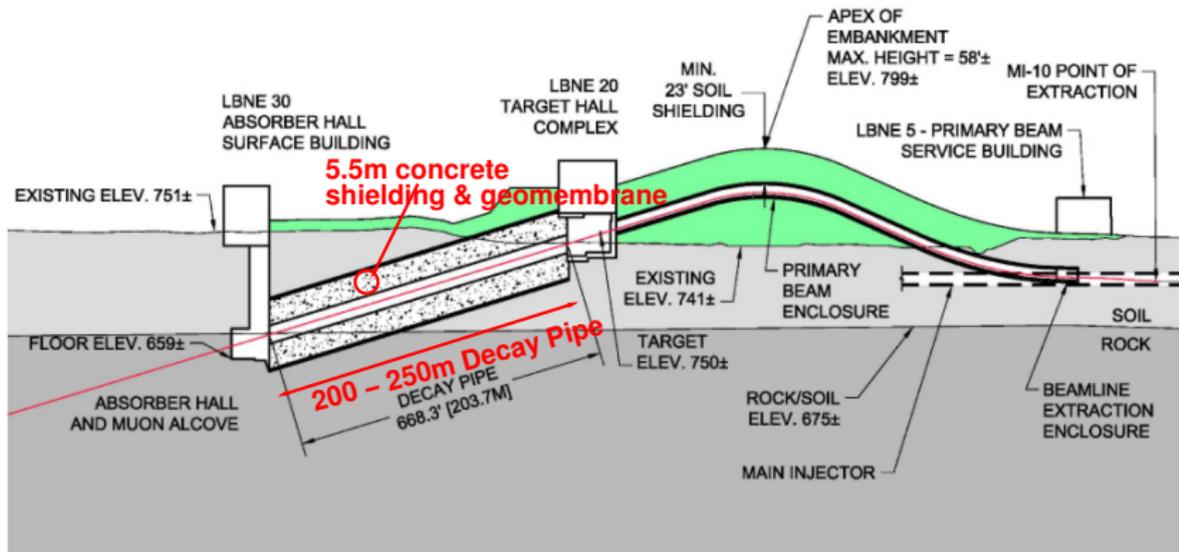
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The LBNE Beamline

Novel beam-on-a-hill construction for 2.3MW from 60-120GeV



**Cost: ~ 390\$M AY (CD1) with 204m decay pipe
(incl 30% cont. and conventional facilities)**

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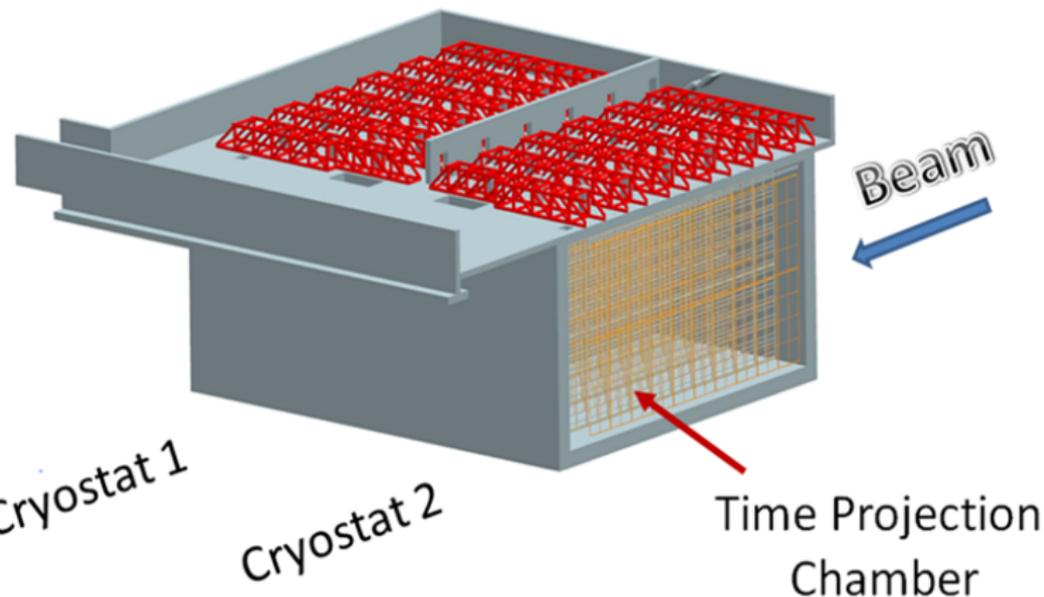
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Conceptual design of CD1 10 kTon



Cost: ~ 260 \$ M AY (incl 40% cont, no CF), Ready 2022

Extra cost to go underground: ~ 135 M\$

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Conceptual design of 35 kTon Underground

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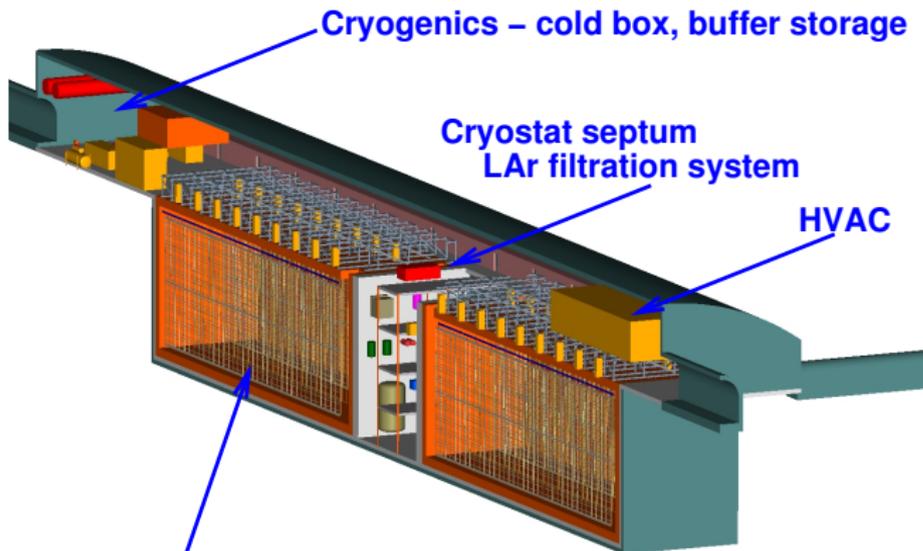
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Detector Module
2 high x 3 wide x 18 long drift cells x 2 modules
216 APAs, 224 CPAs

35 kton (underground) : ~ 660\$M FY10\$ (incl. 40% contingency)

ν_e Appearance Signals in LBNE 35 kton LAr-TPC with 2.3MW 80 GeV

L. whitehead, UH

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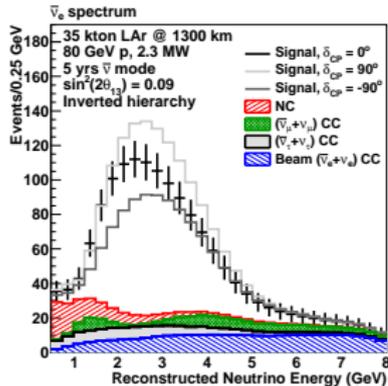
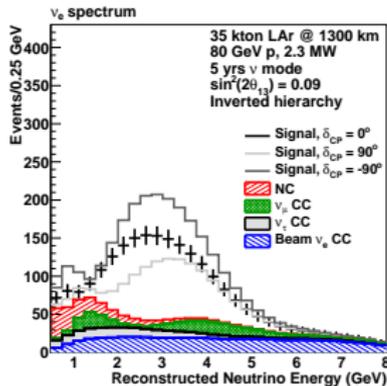
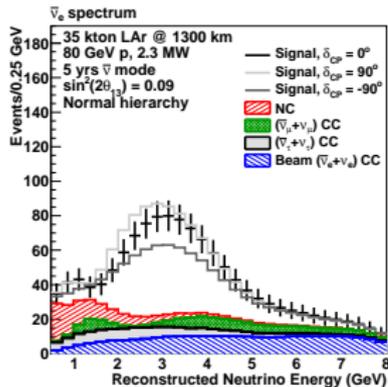
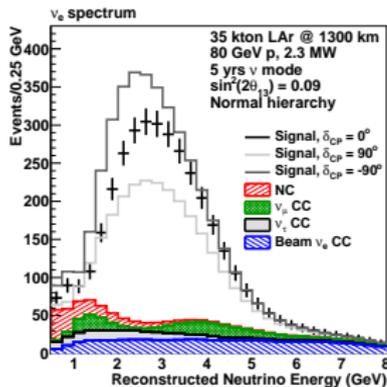
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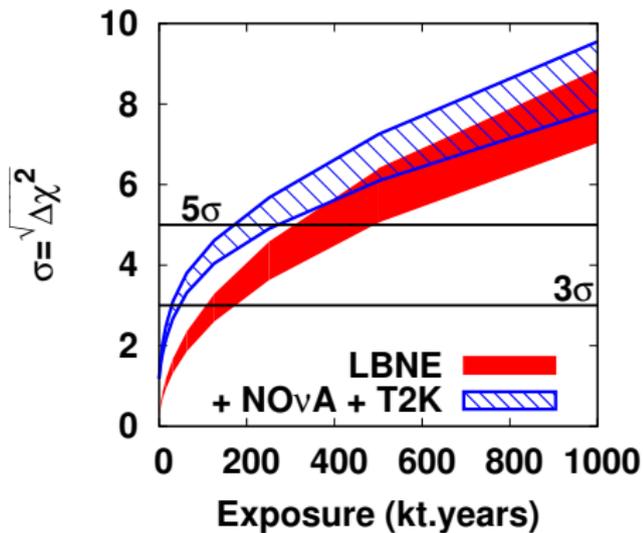
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Bass, CSU

Band: modest beam improvements! - big impact on sensitivity

Mass Hierarchy Sensitivity Worst case



Need 100kt.yrs at 700kW to resolve MH with $\geq 3\sigma$

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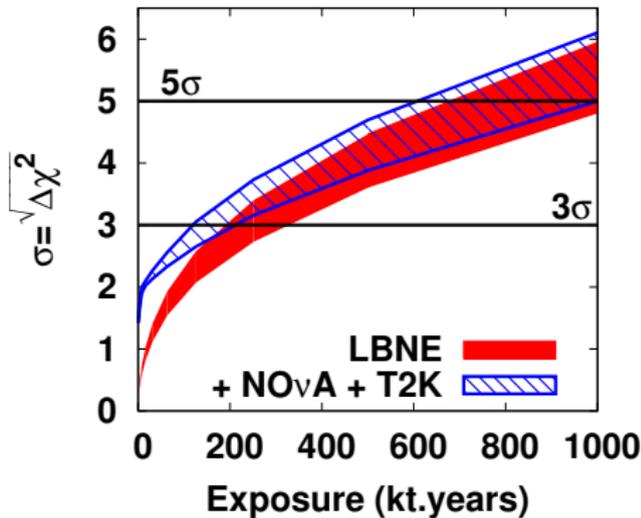
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Bass, CSU

Band: modest beam improvements! - big impact on sensitivity

CP Violation Sensitivity 50% δ_{CP} Coverage



Need 200kt.yrs at 700kW to resolve CPV with $\geq 3\sigma$ for 50% δ_{CP}

CSU

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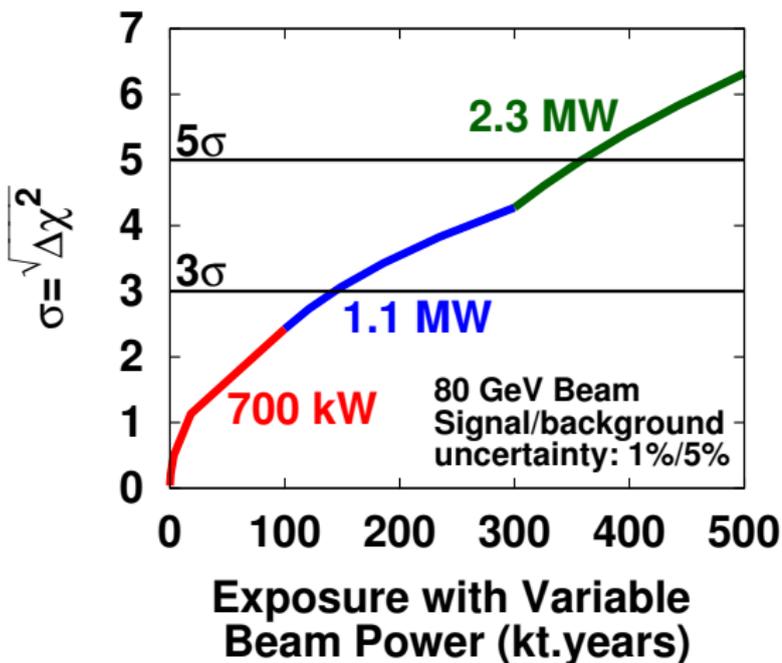
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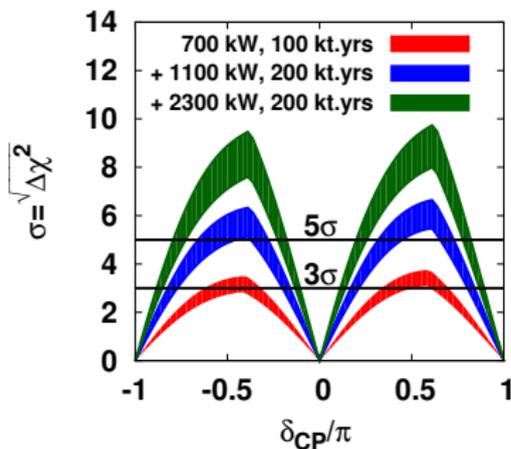
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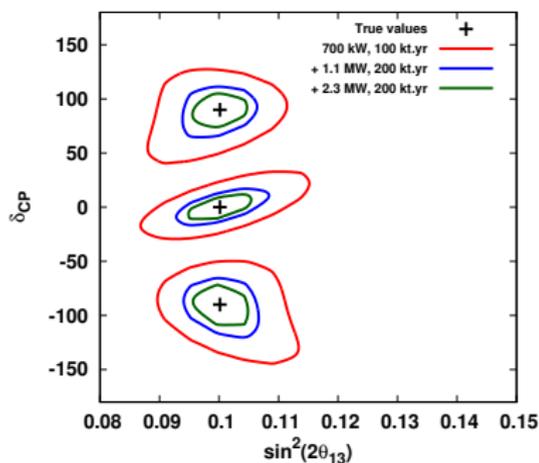
CP Violation Sensitivity 50% δ_{CP} Coverage



CP Violation Sensitivity



Project X Staging 1:1 $\nu:\bar{\nu}$, 1%/5% Signal/BG systematics



With sufficient exposure we can reach 5 – 10° resolution on δ_{CP} .

Resolution of δ_{cp} : Comparison with other Proposals

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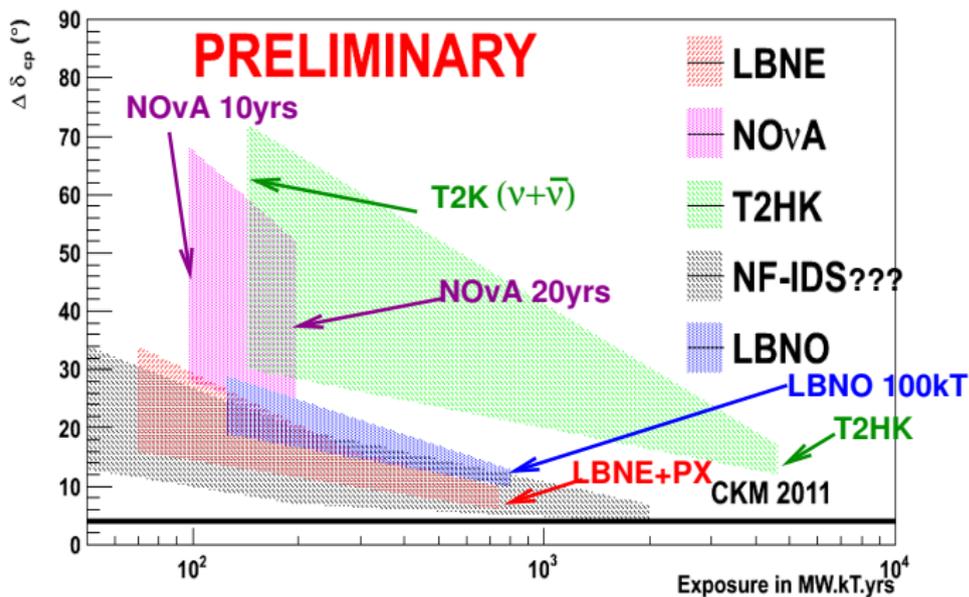
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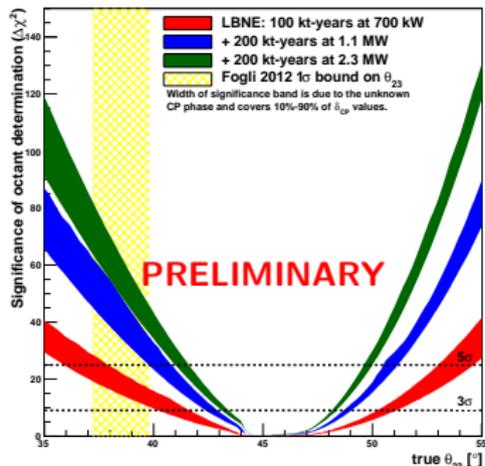


**Very long baseline superbeams (or NF) with MT.MW.yrs
= CKM precision**

Resolving the θ_{23} octant:

(E. Worcester)

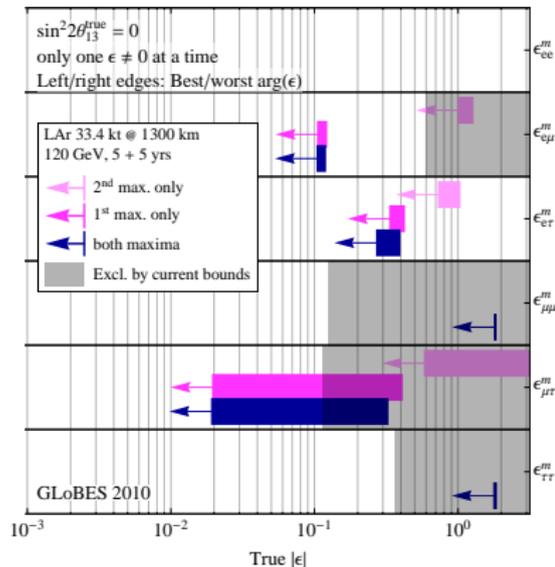
Octant Sensitivity



Sensitivity to new physics:

(J. Kopp)

NC NSI discovery reach (3σ C.L.)



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Two proposals to use low energy multi-MW beams to probe CP violation at the 2nd maximum using massive water Cherenkov detectors:

“Proposal for a neutrino Super Beam using the ESS 5 MW, 2.5 GeV linac as proton driver” M.Dracos and T. Ekelof

“Precision Neutrino Oscillation Measurements using Simultaneous High-Power, Low-Energy Project-X Beams” M.Bishai, M.Diwan, S.Kettell, J.Stewart, B.Viren, L.Whitehead, E.Worcester, arXiv 1203.4090

Project X will allow SIMULTANEOUS multi-MW 8 GeV and 60 GeV.

Work is progressing on 2nd maximum CP measurements

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SUMMARY AND CONCLUSIONS

The 3 flavor framework for neutrino oscillations is well established

- What is the mass ordering (hierarchy) of the 1 and 3 mass states? Is CP violated in neutrinos? Is the mixing between 2-3 states maximal?
- The measurement of the hierarchy using the matter effect in long baseline accelerator $\nu_\mu \rightarrow \nu_e$ is the most effective technique.
- Baselines of > 1000 km are needed to cleanly separate CPV effects from matter effects AND new physics.
- Discovering ν CPV requires many 100kt .MW .yr exposures! . Multi MW proton beams with energies $\sim 50 - 60$ GeV are optimal for the LBNE baseline.
- CPV effects are largest at 2nd osc. max. . Proton beams ≥ 4 MW at 3-8 GeV matched to 100kT detectors at 1100-1300km on-axis can probe this region.
- *The LBNE experiment has the 1) optimal baseline, 2) multi-MW beam design and 3) best detector technology. LBNE phase I preserves all 3 features. With additional partners, phase 1 would include a larger underground detector and a near detector.*

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Thank you